

Strain-rate dependency of strength of soft marine deposits of the Gulf of Mexico

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Abstract: Many marine civil engineering applications require knowledge and understanding of the behavior and strength properties of soft cohesive marine sediments under high strain-rate conditions, typically encountered during impact penetration events of sediment probes and other objects as a result of free fall through the water column. In order to investigate these effects, a series of variable rotational rate vane shear tests were performed using a precision rheometer and spanning the rotational rate range of 0.25 to 1000 [1/min]. A wide range of water contents from 65 to 95% was examined as a primary influence on the response of a particular saturated silty clay material. Non-linearities in the behavior of the soft mud were analyzed and applicability and precision of various models examined. A modified rate equation is suggested yielding good correlation with experimental data at all water contents and all rotational rates explored.

I. INTRODUCTION AND BACKGROUND

A variety of offshore applications in both civilian and military areas of interest require a fundamental understanding and detailed knowledge of the strength and deformability characteristics of marine sediments. Soft cohesive (clayey) sediments are often characterized by low undrained shear strength and non-linear strength dependency on the rate of loading. Design of many structures founded, placed, or embedded into these sediments represents a particular challenge. One of the common methods of evaluating strength, as employed by the Navy as well as by the civilian engineering sector, is based on the deployment of dynamic penetrometers. These probes are often deployed in free-fall through the water column and impact and penetrate the seafloor sediments in free fall. Various algorithms that derive the undrained shear strength of the sediment from the deceleration records of such probes utilize some form of strain-rate dependency, without which the strength estimated may be quite inaccurate. Several current algorithms, employed in processing the impact records of dynamic penetrometers, such as XBP (eXpendable Bottom Profiler) and STING (Sea Terminal Impact Naval Gauge), do not perform well and are thus in need of improvement. Typical impact velocities could range up to 10 m/s. However, fundamental understanding, based on controlled tests, of behavior at these strain rates is scarce.

A number of previous studies, *e.g.* [1-8], addressed the phenomenon of strain-rate dependency of the undrained shear strength and viscosity but most have focused on traditional terrestrial geotechnical applications and thus few have spanned the range of strain rates characteristic of the marine dynamic penetration events. Thus, the goal of this study is to systematically analyze the dependency of the undrained shear strength on the rate of loading in the ranges that have received little attention to date. To attain this goal, a series of variable rotational rate vane shear tests has been performed on reconstituted specimens of soft marine mud from the Gulf of Mexico.

The vane test may not always be the most accurate method of describing the undrained shear strength, mainly because it is not a test performed on an elementary soil volume under controlled stress (or strain) conditions, and may suffer from ambiguities of stress distribution during shear and uncertainties about the location and the exact size of the shearing zone. It is, however, a widely used test in typical offshore civil engineering and Navy applications and is often the only strength test practicable. The vane is nevertheless known to produce good results particularly in water saturated cohesive marine sediment, which is the focus of this investigation.

Several models may be used to describe the strain-rate dependency of undrained strength, including an inverse hyperbolic sine law:

$$S_U = S_{U,ref} \left[1 + \lambda' \operatorname{arcsinh} \left(\frac{\dot{\gamma}}{\dot{\gamma}_{ref}} \right) \right], \quad (1)$$

a logarithmic law:

$$S_U = S_{U,ref} \left[1 + \lambda \log_{10} \left(\frac{\dot{\gamma}}{\dot{\gamma}_{ref}} \right) \right], \quad (2)$$

or a power law:

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14. ABSTRACT Many marine civil engineering applications require knowledge and understanding of the behavior and strength properties of soft cohesive marine sediments under high strain-rate conditions, typically encountered during impact penetration events of sediment probes and other objects as a result of free fall through the water column. In order to investigate these effects, a series of variable rotational rate vane shear tests were performed using a precision rheometer and spanning the rotational rate range of 0.25 to 1000 [1/min]. A wide range of water contents from 65 to 95% was examined as a primary influence on the response of a particular saturated silty clay material. Non-linearities in the behavior of the soft mud were analyzed and applicability and precision of various models examined. A modified rate equation is suggested yielding good correlation with experimental data at all water contents and all rotational rates explored.						
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$$S_U = S_{U.ref} \left(\frac{\dot{\gamma}}{\dot{\gamma}_{ref}} \right)^\beta \quad (3)$$

where S_U is the undrained shear strength at the current strain rate $\dot{\gamma}$, $S_{U.ref}$ is the undrained shear strength at some reference strain rate $\dot{\gamma}_{ref}$, and λ , λ' , and β are material constants.

The primary variable, representing the shear strain rate, is typically chosen as either the rotational rate of the vane (*e.g.* as in [9]) or the peripheral velocity of the vane (*e.g.* as in [7]). Reference [7] presents results collected from several studies, showing the general dependency of the undrained shear strength on the rate of loading (peripheral velocity in this case), shown in Fig. 1.

The power-law dependence was selected as representing the data best, although it is evident that experimental results have a tendency of deviating from this relationship at higher values of the peripheral velocity. This suggests that the constant chosen (β in this case) may begin to vary in this range. Similar observations were made earlier in [4].

One of the goals of this study is to extend the experimental data into higher strain (or velocity) range, approaching the values characteristic of impact burial and penetration events, as was mentioned earlier.

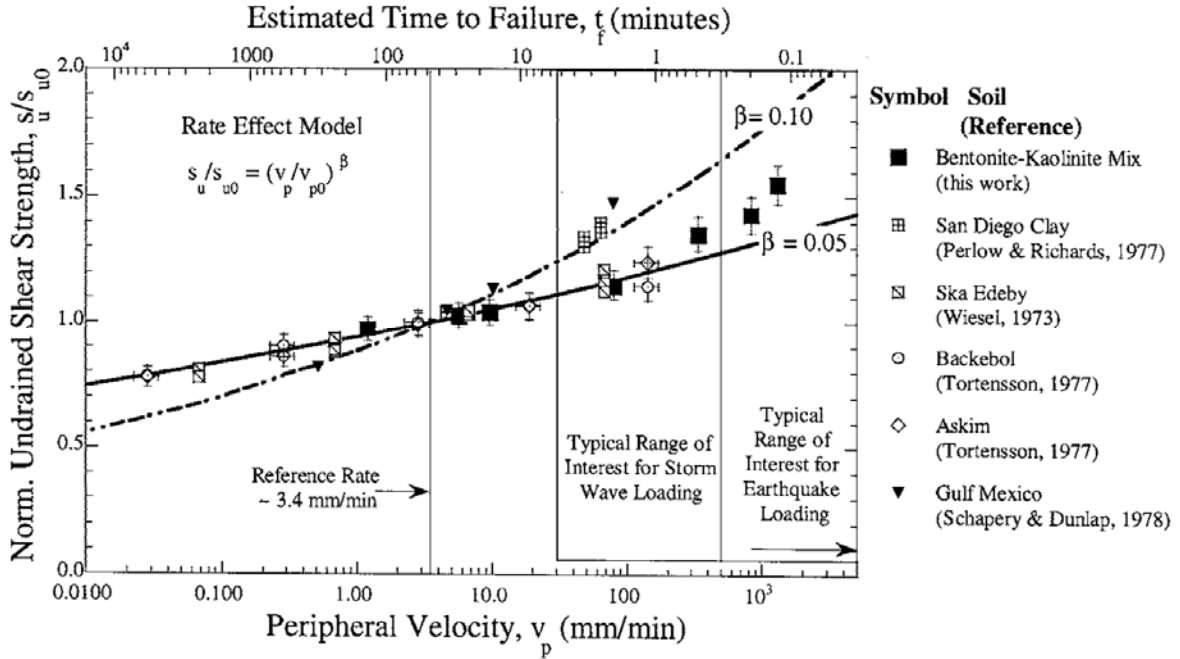


Fig. 1. Influence of the peripheral velocity of the vane on the undrained shear strength (from [7])

II. EXPERIMENTAL SETUP

A commercial rheometer (BrookfieldTM) was chosen to perform the variable rotational rate vane tests, shown in Fig.

2. The particular configuration selected is referred to as the Soft Solids Tester (SST).



Fig. 2 Brookfield™ R/S Soft Solids Tester (rheometer) with vane attached

This device has a number of vanes of different sizes available for shear strength testing. We selected a 10x20 mm vane, as it is a common size used in routine testing of soft sediments retrieved from a variety of undisturbed marine samplers, *e.g.* gravity corers. This device has the torque capacity of 0.05 to 50 mNm and a rotational velocity range of 0.01 – 1000 rpm. The device torque capacity, when used with a 10x20mm vane translates to the shear strength range of, approximately, 0.4 to 14 kPa.

III. SOIL TESTED

The soil selected for this testing program was the same as used in [10]. This is a typical soft sediment from the Gulf of Mexico with a dominant fine grain, or “mud” fraction, as described in Tables 1 and 2, and Fig. 3. The soil has the natural water content of 69% and it was reconstituted for testing at water contents of 55, 65, 75, 85, and 95%.

Sand 4.75-0.075 mm	Mud <63 μm	Silt 75-2 μm	Clay < 2 μm
26 %	62 %	31 %	32 %

TABLE 1. GRAIN SIZE CHARACTERISTICS OF THE SEDIMENT TESTED

LL	PL	PI	natural water content	- #200	ACT
%	%	%	%	%	-
43	20	23	69	74	0.71

TABLE 2. PLASTICITY CHARACTERISTICS OF THE GULF OF MEXICO MUD TESTED

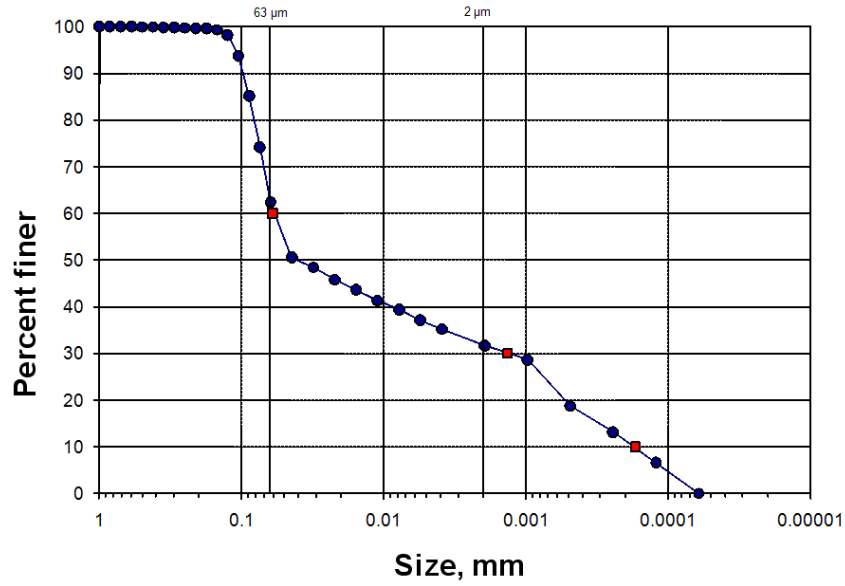


Fig. 3. Grain-size curve of the Gulf of Mexico mud tested

IV. EXPERIMENTAL RESULTS

Basic results from the series of the variable rotational rate vane tests are presented in Figs. 4 and 5, showing the evolution of the torque as a function of the overall angular displacement of the vane. Only results for the soil with 55% water content are shown here for brevity. The same data are presented in both figures, with angular displacement plotted once on the linear scale (Fig. 4) and once on the logarithmic scale (Fig. 5), in order to accentuate the tests of shorter duration. Most curves show distinct maximum and then, a gradual decline to some residual value. Most tests appear to have reached an apparent residual resistance.

There are a number of difficulties in conducting vane tests under an increasingly higher rotational rate, in general. Primarily, the device needs to be able to (a) apply the torque to the vane at the speed compatible with the requested velocity and (b) be able to acquire the data from the torque load cell commensurate with the requested speed. The device used in this study, Brookfield R/S SST, has proved capable in applying the torque, but has a built-in limitation on the speed of the device data acquisition. As is evident from Figs. 4 and 5, only in slower tests is the torque noticeably rising to the peak value and then dropping to some residual one. It is possible (although we consider this unlikely) that the peak may have been reached earlier, before it could be acquired by the device and recorded, in tests with higher rotational velocity. This can only be demonstrated for certain if similar tests are done using a device that allows for a much faster data acquisition as well as actual torque application and minimizing the device inertial effects.

The results show a regular pattern of peak strength evolution with increasing rotational rate, from 0.25 to 1000 rpm. When we consider the peak value of the torque recorded (as corresponds to the undrained shear strength), the rate dependency can be shown clearly as a function of soil water content in Fig. 6. If the values of the undrained shear strength are calculated and plotted vs. log of the vane rotational rate (expressed in rad/s, as in Fig. 7) we can observe the trends similar to those in [7]. We may also notice that at higher rates and higher water content, the curves begin to deviate significantly from the approximately linear trends that could otherwise be well represented by a logarithmic fit function.

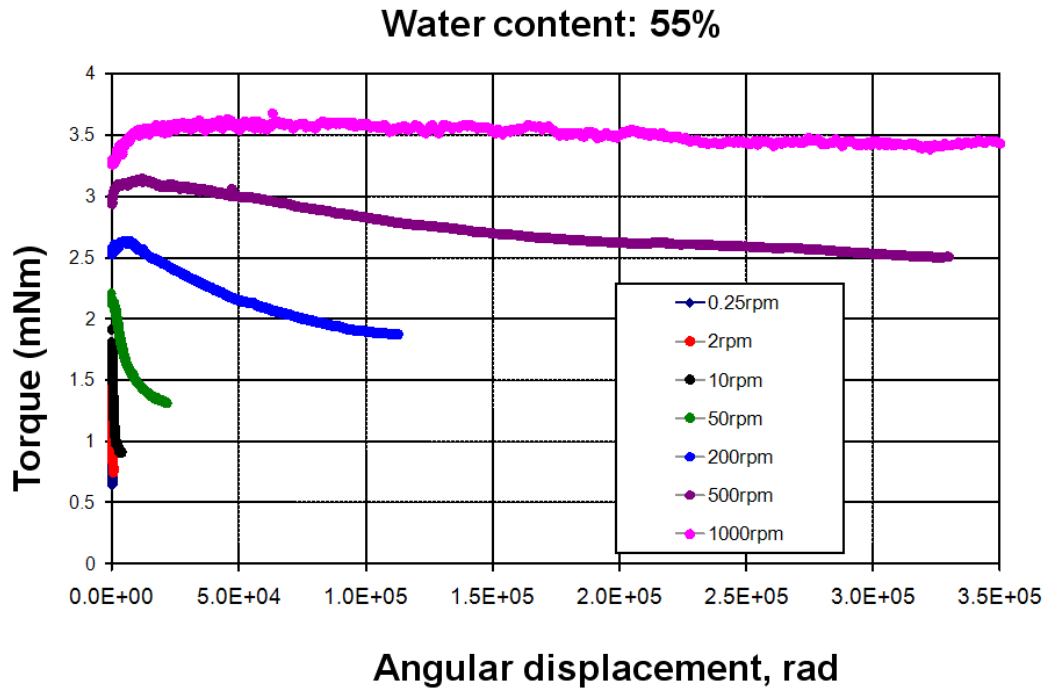


Fig. 4. Torque vs. angular deformation on the linear scale in reconstituted soil with 55% water content and variable vane rotation rates

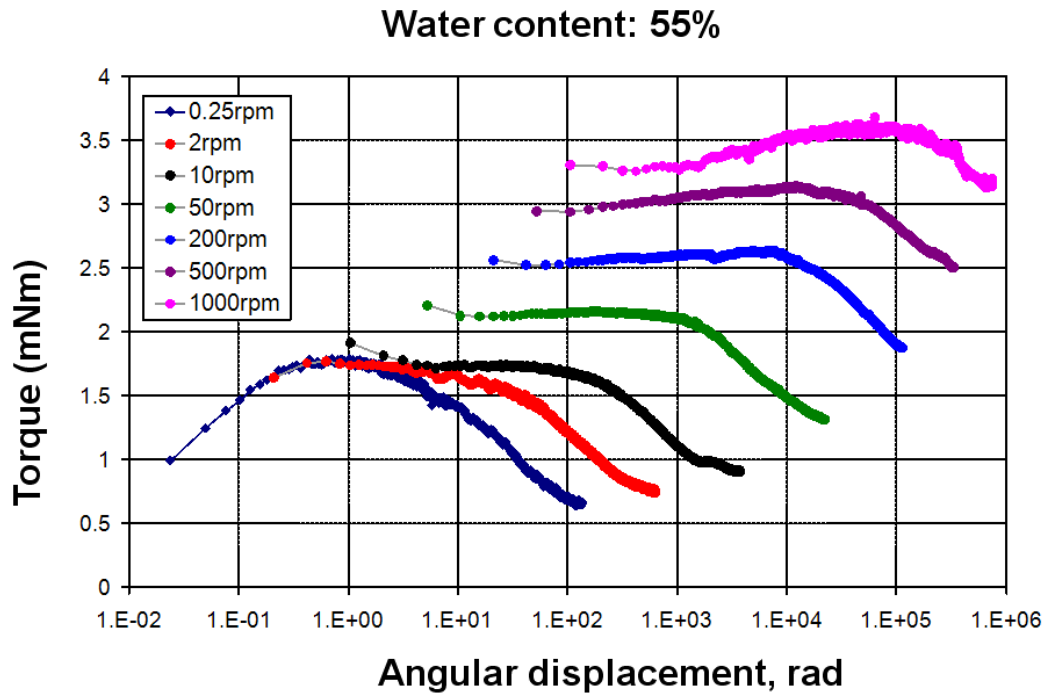


Fig. 5. Torque vs. angular deformation on the logarithmic scale in reconstituted soil with 55% water content and variable vane rotation rates

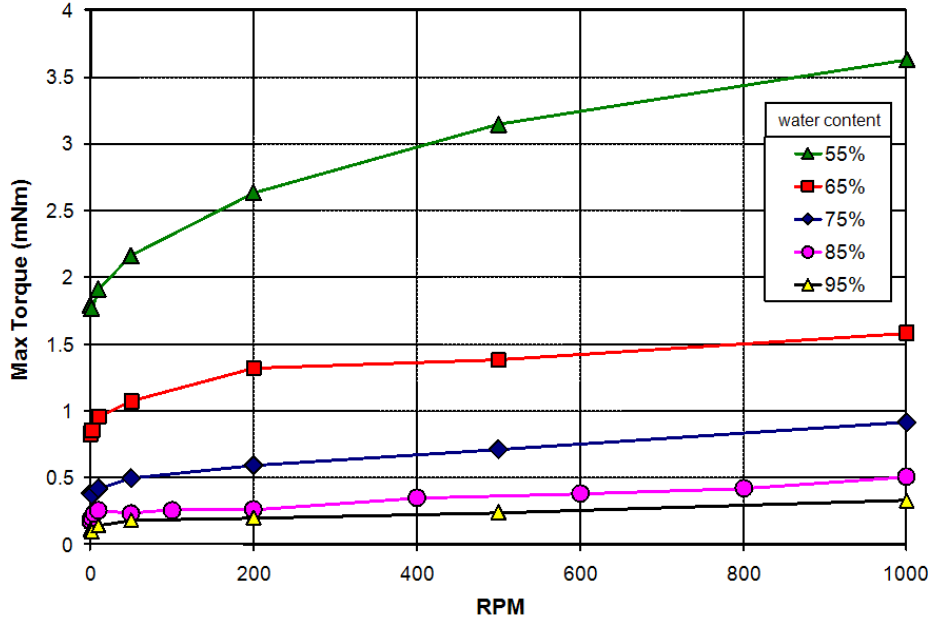


Fig. 6. Maximum torque as a function of rotational rate and soil water content

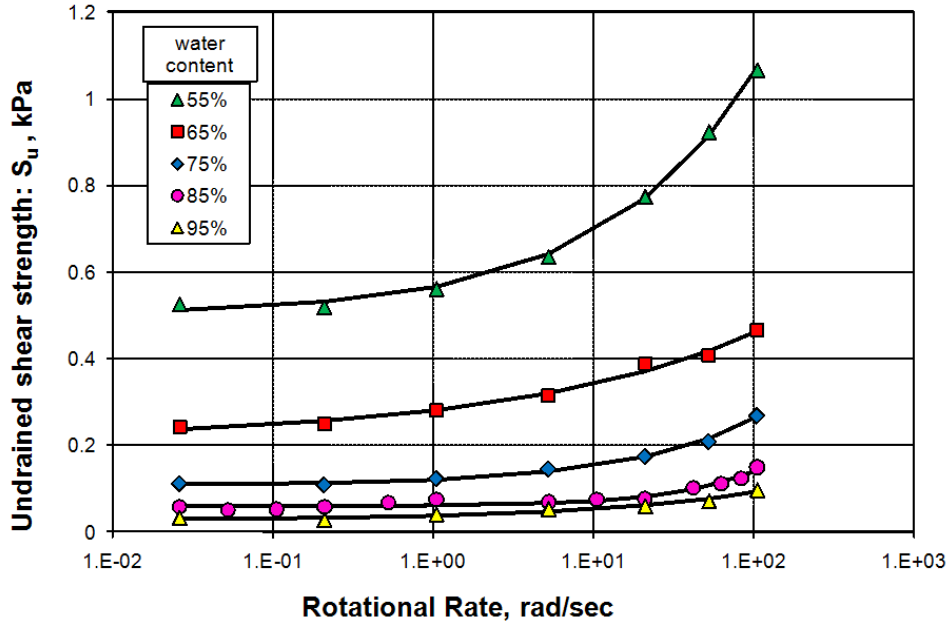


Fig. 7. Variation of undrained shear strength with rotational rate and water content

V. MODELS

Analysis of the data presented and comparison with other studies (*e.g.* [11]) shows that the trends, present at lower rotational velocities may begin to change at those greater than 10 rad/s. We shall now examine the applicability of several models, given in Eqs. (2) - (1) to fit our data. We shall view the application of these models to the case of the 55% water content series, as a representative case. We shall then show the best fits selected for all other cases for validation.

It may be easier to analyze the various equations by applying them to the normalized properties, thus using $S_U / S_{U,ref}$ vs. ω / ω_{ref} , where ω is the rotational vane velocity, the lowest value of which (0.25 rpm) is selected as the *reference* rotational velocity. First, the following models are used, similar to Eqs. (2) - (1):

$$\frac{S_U}{S_{U.ref}} = 1 + b_1 \operatorname{arcsinh}\left(\frac{\omega}{\omega_{ref}}\right), \quad (4)$$

$$\frac{S_U}{S_{U.ref}} = 1 + b_2 \log_{10}\left(\frac{\omega}{\omega_{ref}}\right), \quad (5)$$

$$\frac{S_U}{S_{U.ref}} = \left(\frac{\omega}{\omega_{ref}}\right)^{b_3}, \quad (6)$$

where b is the free constant. Fig. 8 shows a series of fits, suggesting that the above equations may not represent the best fits in our case. Then we examine a possibility of using a modified power function, constrained to give $S_U / S_{U.ref} = 1$ as the normalized rotational rate approaches zero:

$$\frac{S_U}{S_{U.ref}} = 1 + b_4 \left(\frac{\omega}{\omega_{ref}}\right)^c, \quad (7)$$

where b, c are material constants that can be determined by least square minimization method. This modified criterion produces a markedly better fit to our experimental data but it also involves an additional material constant. The parameter space now includes: S_U , $S_{U.ref}$, b_4 , and c . This model results in the best fit to the data. If, however, material constants are to be minimized in number, we could fix the constant c at 0.5:

$$\frac{S_U}{S_{U.ref}} = 1 + b_5 \left(\frac{\omega}{\omega_{ref}}\right)^{0.5} \quad (8)$$

with only minor decay in the quality of the fit, as can also be seen in Fig. 8. Fixing this constant works well in our data set. It cannot be assumed, however, that this value of $c = 0.5$ will also apply to a different material without acquiring additional experimental data.

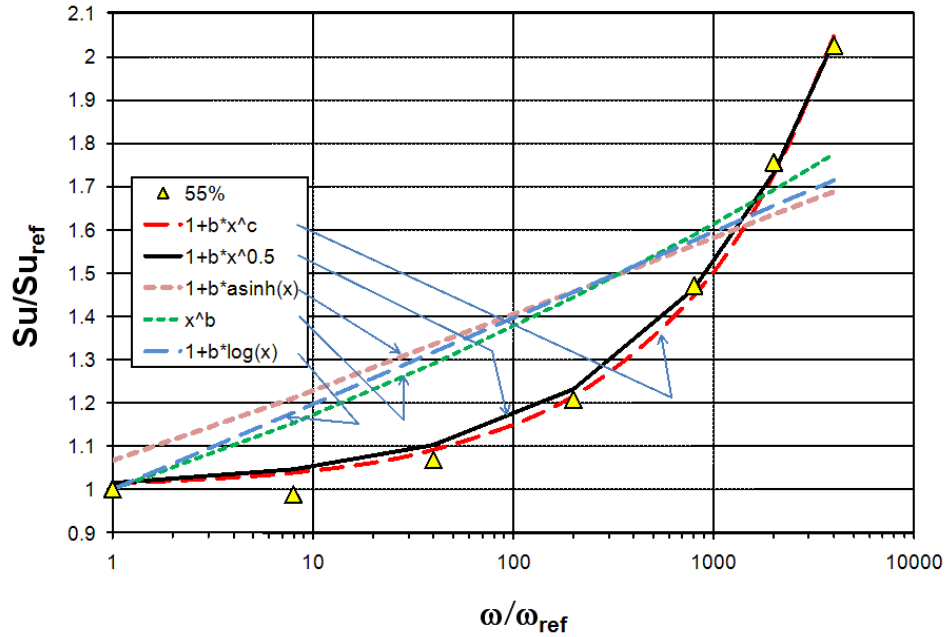


Fig. 8. Normalized shear strength vs. normalized rotational rate. Models for 55% water content

The ability to produce excellent fits with our experimental data for all water contents examines is demonstrated in Fig. 9. Fig. 10 shows only the fitted curves without the experimental data for clarity. The overall trend with the changing water content is evident, even if slightly irregular, perhaps due to the relative small water content increments between experimental series (10%), as well as other possible inaccuracies in actually maintaining the pre-set water values throughout the test.

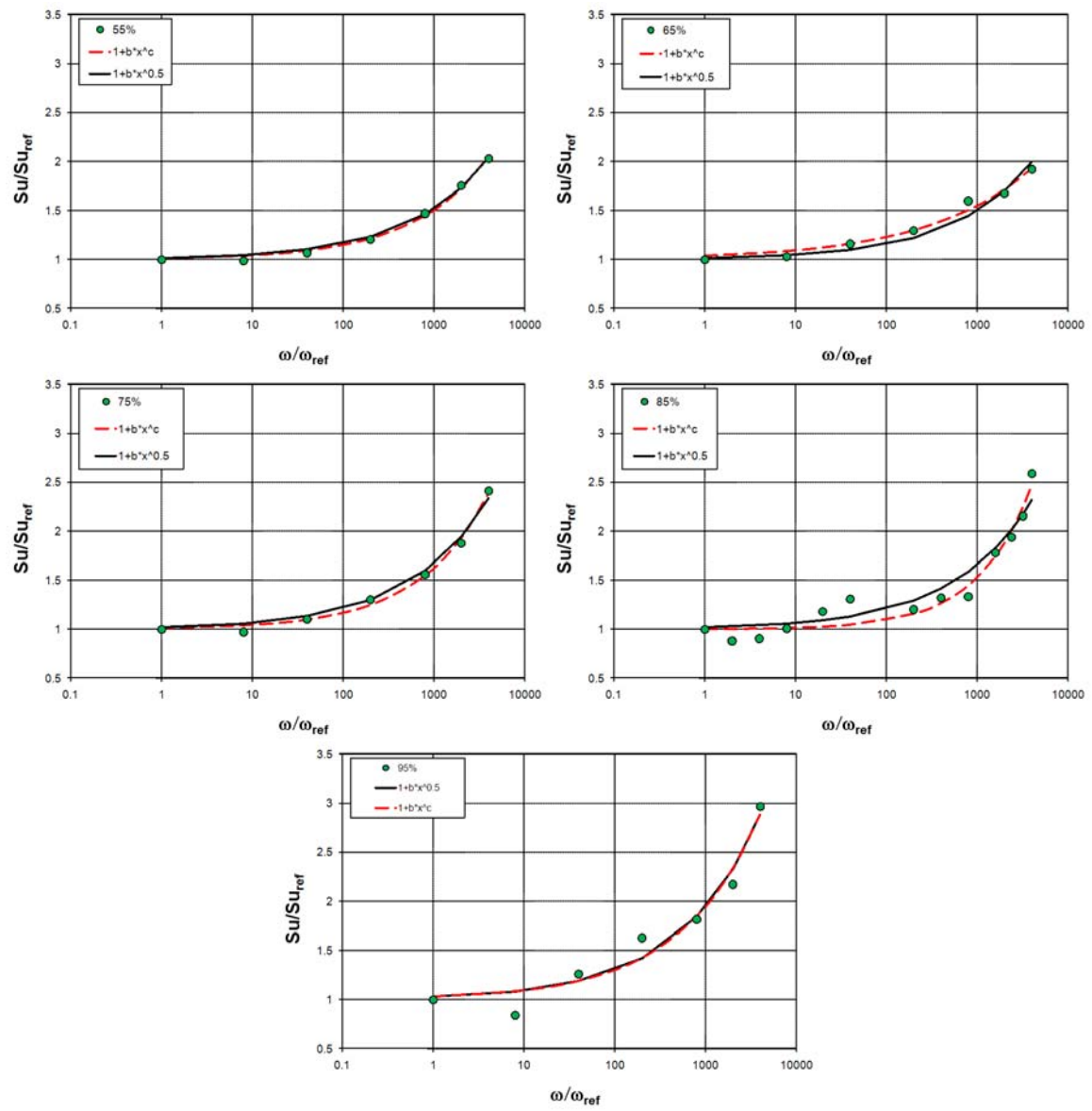


Fig. 9. Power and modified power fits for 55, 65, 75, 85, and 95% water content

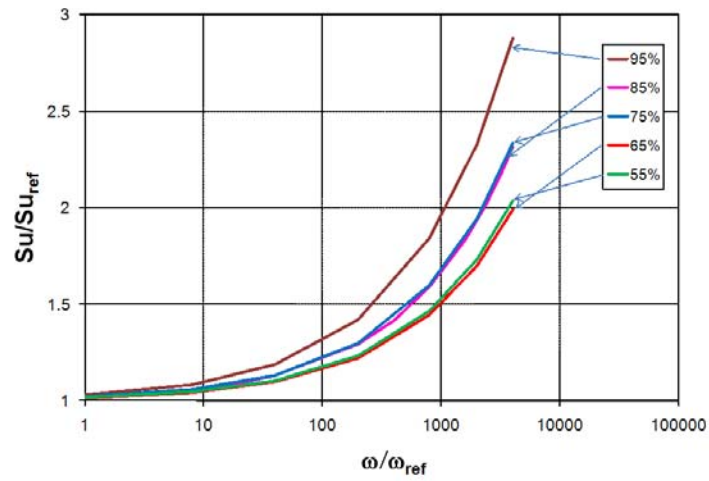


Fig. 10. Modified power fits for all water contents

VI. CONCLUSIONS

This paper presents the results of series of variable rate vane tests utilizing Brookfield™ R/S SST device (rheometer). Reconstituted specimens of Gulf of Mexico mud were tested at water contents of 55, 65, 75, 85, and 95%. The standard 10x20mm vane was used and rotational rates varied between 0.25 and 1000 rpm (device limit). The main goal of the study was to examine the applicability of the current strain-rate models of the undrained shear strength dependency of clayey materials under higher rates. Our findings include the fact that only at the lower rotational rates of, perhaps less than 10 rad/s (or even lower) did the conventional logarithmic or power relationships worked well. It appears that the modified power law (with or without an additional material constant) produce a significantly better fit to the experimental data in our strain rate range of interest.

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